Table 1: Radiation parameters and modeled contributions to the global solar and thermal TOA forcings for individual particle sizes. For the individual particle sizes extinction efficiencies Q_{ext}, single scattering albedos ω_0, and asymmetry parameters g are given for the example of the solar wavelength $0.55\,\mu$m. A refractive index of $1.56 + 0.006i$ at this wavelength was used [9]. Uncertainties in the refractive index are of order 40% [10]. The percentage of contribution of individual particle sizes to solar and thermal dust forcing is given for total dust.

Effective Radius [μm]	Q_{ext} [0.55 μm]	ω_0 [0.55 μm]	g [0.55 μm]	Fraction of TOA Solar Forcing [%]	Fraction of TOA Thermal Forcing [%]
0.1	0.644	0.964	0.515	2.4	0.3
0.2	2.316	0.973	0.663	27.1	2.0
0.4	3.086	0.956	0.666	52.5	6.0
0.8	2.583	0.907	0.688	28.8	18.7
1	2.476	0.887	0.716	2.3	68.4
2	2.280	0.816	0.797	-10.9	4.7
4	2.174	0.724	0.857	-4.2	1.0
8	2.110	0.633	0.904	-1.1	0.3

FIGURE 1: Longitudinal mean radiative forcing resulting from the GISS GCM at top of atmosphere for the "best estimate" dust distribution (reference 3). Positive numbers describe increased incoming or decreased outgoing radiation. Compared are: (a) the solar and thermal components of the dust forcing with the resulting total forcing, (b) the dust forcing for clear and cloudy sky conditions, and (c) forcing for clear sky only for total dust and dust from disturbed sources [4] at top of atmosphere and surface. Note that the scale of Figure 1c is different from the scale of Figures 1a and 1b.

FIGURE 2: Map of surface forcing of dust from disturbed soils (a) compared with forcing caused by anthropogenic increase in greenhouse gases (CO_2, CH_4, N_2O and CFC's) and sulfate aerosols (b). For the combined forcing (c) the dust forcing was added to the anthropogenic greenhouse and sulfate forcing.

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increased heating rates between 1.6 and 15.6 K day^{-1} for a dust optical thickness of 1.5 at 0.55 μm wavelength. This additional atmospheric heating may influence atmospheric stability in regions with high dust loading, and lead to modifications of atmospheric circulation patterns and regional climate.

To improve estimates of the radiative forcing and to assess uncertainties, additional laboratory, field, and satellite measurements are required. The laboratory measurements must include complex refractive indices for especially submicron-size dust from different source regions. The refractive indices must cover all wavelengths of the full solar and thermal spectra. The satellite observations should make use of spectrally-resolved upwelling radiation to distinguish amongst aerosol types and to retrieve optical depths.

To fully assess the magnitude and the climatic implications of disturbed soil mineral dust requires a fully interactive GCM where the dust heating effects are allowed to influence atmospheric dynamics. Furthermore, since both the sources and the removal of dust are directly dependent on local climate, the changes in radiative forcing by dust may induce changes in the hydrological cycle and in regional circulation patterns that lead, in turn, to further changes in the dust sources and sinks. Thus there is a strong potential for highly interactive feedback effects.

at TOA nearly cancel strongly suggests that mean radiative forcing at TOA does not provide sufficient information to fully characterize the aerosol effect on climate.

Radiative forcing at the surface by dust from disturbed sources (Figure 2a) is negative, as both the absorption and reflection of solar radiation by the dust reduce the solar radiation incident at the ground. The global mean forcing at the ground due to dust from disturbed sources is -0.96 W/m^2, with a maximum of -25 W/m^2 occurring over the Arabian Sea. If the contributions from anthropogenic greenhouse gas and sulfate forcings (Figure 2b) are added, the resulting global mean flux at the surface is reduced to -0.6 W/m^2 (Figure 2c) compared to +0.4 W/m^2 for the case of only anthropogenic greenhouse gases and sulfate. Thus, dust from disturbed sources actually changes the sign of the global mean anthropogenic forcing at the surface. It is not possible to translate the uncertainties of the model input parameters (global mean source strength, percentage dust from disturbed soils, refractive indices) directly into uncertainties of the radiative forcing because the global distribution of the radiation input parameters (refractive indices, sub-micrometer dust size distribution) is not well known and thus a meaningful range of uncertainty can not be given based on the few existing measurements.

Changes in the atmospheric dust load also changes the atmospheric heating rates. An increase in longitudinal mean heating rate of 0.04 $K\,day^{-1}$ occurs between 10 and 30°N corresponding to the location of maximum dust load. The maximum heating caused by disturbed dust is about 2 $K\,day^{-1}$, which is in good agreement with the estimates of [3] and [21] who estimated

To put the radiative forcing by disturbance dust in context with the forcings by greenhouse gases and industrial sulfates we use the greenhouse forcing due to increases in CO_2, CH_4, N_2O and CFC's during the industrial era as calculated in the GISS GCM [17]. The global and annual mean forcing due to the increase in anthropogenic greenhouse gases that occurred from 1850 to 1980 is about $+2.1\,\mathrm{W/m^2}$ with an uncertainty of about 10%.

Estimates of sulfate forcing are based on the regional pattern of anthropogenic sulfate distribution [18] and radiative parameters described in [17]. The forcing can vary by more than a factor of 2 depending on different assumptions regarding the global sulfate burden and seasonal variations [19]. To facilitate comparison with other forcings and other studies, we scaled the resulting annual and global mean instantaneous sulfate forcing derived by the GISS GCM to a value of $-0.28\,\mathrm{W\,m^{-2}}$, which is equal to the value given by [20].

In contrast to greenhouse gases, which have a positive thermal forcing effect, and sulfate aerosols, which cause negative solar forcing, dust forcing at solar wavelengths can produce either positive or negative forcing depending on clear/cloudy sky conditions and on surface albedo. Dust forcing at thermal wavelengths is always positive. The resultant total TOA radiative forcing by disturbance dust ranges from $-2.1\,\mathrm{W/m^2}$ to $+5.5\,\mathrm{W/m^2}$ locally. The global mean net forcing at TOA calculated for wind-blown mineral dust is relatively small with a mean value of $+0.14\,\mathrm{W\,m^{-2}}$ for total dust and $+0.09\,\mathrm{W\,m^{-2}}$ for dust from disturbed sources. This can be compared to the combined anthropogenic greenhouse gases and SO_4 forcing of $+1.8\,\mathrm{W/m^2}$ in the global mean [20]. The fact that the solar and thermal radiation forcings increasingly positive for particles larger than 1 μm, since the larger particles absorb more strongly at solar wavelengths [14, 16]. The outgoing thermal radiation is dominated by particles with an effective radius of 1 μm since the smaller particles have smaller extinction coefficients and larger particles have short atmospheric lifetimes.

Figure 1b separates the total TOA dust forcing into clear–sky and cloudy–sky contributions. In the longitudinal mean, the clear-sky forcing is essentially negative because the aerosol is more reflecting than the ground surface, while the cloudy-sky forcing is positive due to increased absorption of solar radiation by dust within and above the clouds. The maximum total forcing for clear skies is located at 40°N, even though the maximum dust loading is at 10–30°N. Again, this is is due to the partial cancellation between total forcing over bright desert surfaces and the forcing over the darker oceans.

Figure 1c compares TOA and surface forcing for total dust and dust from disturbed sources only. Surface forcing by is considerably larger than TOA forcing. Dust forcing at TOA is small in the longitudinal mean because of cancellation of the clear and cloudy–sky contributions to the solar forcing. The TOA dust effect would be underestimated if only longitudinal means were considered.

Given the inherent uncertainties in dust refractive indices and particle sizes, the mean TOA forcing by mineral dust could easily be zero (or even slightly negative) if the aerosol particles were somewhat smaller in size or less absorbing. On the other hand, the substantial flux reduction at the surface and the increase in atmospheric absorption are the more robust characteristics of dust impact on climate.

ments defines the instantaneous radiative forcing with no dynamic feedback effects of the added dust load included.

At solar wavelengths, mineral aerosols are partly absorbing, with the single scattering albedo decreasing with increasing particle size [14, 16]. Whether or not the dust absorption results in an increase or decrease of the planetary albedo depends on the dust single scattering albedo as well as on the albedo of the underlying surface and on the cloud cover. Over dark surfaces like the ocean, the dust increases the planetary albedo because backscattering of incident solar radiation of the dust layer exceeds that from the dark surface. On the other hand, over high-albedo surfaces, such as snow or bright deserts, the additional absorption by the dust reduces the solar flux reflected from the surface and results in a net reduction of radiation to space.

Figure 1a shows the solar and thermal components of the top-of-atmosphere (TOA) dust forcing. Solar forcing is mainly negative (cooling), as longitudinally, the surface is darker than the dust. Maximum negative forcing occurs in areas of high dust optical thickness over the Arabian Sea, and to a lesser extent over the North Atlantic off the west coast of Africa. Thermal forcing is always positive as the dust absorption at thermal wavelengths contributes to greenhouse warming. The maxima of solar and thermal forcing occur at different latitudes because solar forcing over the bright Saharan and Arabian deserts and the dark ocean surfaces partially cancel around 20–30°N, where the dust optical thickness is highest. The total solar and thermal forcing is also nearly cancelled in the longitudinal mean.

Table 1 summarizes the global mean fraction of solar and thermal forcing contributed by the different particle sizes. The TOA solar forcing becomes radiative effects were computed using Mie scattering theory for the standard gamma size distribution with effective variance of 0.2 for each size bin for refractive indices reported by [8, 9]. Representative values of the radiative parameters at $\lambda = 0.55\mu$m are given in Table 1. Dust radiative parameters are likely to vary regionally [10], but the lack of detail information about the global distribution of dust chemical composition and of dust refractive indices covering the full solar and thermal spectra prevent quantitative comparisons. While non–sphericity of dust particles can produce large errors in remote sensing applications based on Mie scattering computations, it has been shown by detailed T–matrix calculations that radiative fluxes and albedos utilizing Mie scattering results for equivalent volume spheres retain good accuracy [11].

Reflection, transmission, and absorption of different specified aerosol distributions are calculated using the single gauss point doubling/adding radiative transfer model in the GISS GCM [12, 13, 14]. The correlated k-distribution method used in the GISS GCM to compute absorption by gases and particles is nominally accurate within 1% compared with line–by–line calculations [15]. The radiation model supports a continuous range of aerosol effective radii from 0.1 to 10 μm. The radiative forcing by dust was calculated using the modeled distributions for 8 size classes.

The GCM was first run for one-year without dust aerosols in the atmosphere. It was then re-run for a year with a specified aerosol distribution, with the atmospheric circulation and all other radiative constituents (e.g. cloud optical properties, water vapor) prescribed by the no-dust experiment. The difference in the radiative fluxes between the aerosol and no-aerosol experi-

ing of atmospheric dynamics. These findings suggest that mineral dust from soil disturbances should be included among the climate forcing factors that are influenced by human activities.

Global dust distributions were calculated with a global model of the dust cycle [5, 4] where dust emissions for eight particle size classes are parameterized in terms of soil moisture, surface wind speed, soil texture, vegetation, and soil surface conditions. Each size class is transported in the Goddard Institute for Space Studies three-dimensional atmospheric tracer transport model [6, 7], and removed from the atmosphere at different rates by gravitational settling, turbulent mixing and rain-out. The model–derived global dust source strength is $1500 \pm 700\,\mathrm{Mt/yr}$ for particles $< 10\mu$m. Dust optical thicknesses are calculated from the modeled space-time distributions of dust mass loading and size distributions [5].

Retrievals of total atmospheric optical depths over the oceans from the AVHRR on NOAA orbiting satellites are used to constrain the modeled source hypotheses [4]. AVHRR features such as the seasonal shift of the Saharan/Sahelian dust plume and the relatively small contribution of dust from Australia cannot be reproduced if the dust aerosol is assumed to originate from natural sources only. They can be best explained with a scenario where $50 \pm 20\,\%$ of the total atmospheric dust load is from disturbed soils that are affected by human impacts or shifts in climate conditions. The resulting annual global mean optical thickness of the total dust load is 0.034, of which disturbed soils contribute 0.017.

Radiative properties (extinction efficiency, single scattering albedo, and asymmetry parameter) of aerosols are size and wavelength dependent. The

The Influence of Mineral Aerosols from Disturbed Soils on Climate Forcing

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Aerosols influence the global radiation budget [1]. Therefore, changes in the atmospheric aerosol load due to either natural causes or human activity will contribute to climate change [2]. Wind–blown mineral dust contributes a major part of the tropospheric aerosol mass loading and its radiative forcing can be locally significant [3]. Model calculations indicate that $50 \pm 20\,\%$ of the total atmospheric dust mass originates from disturbed soils [4], i.e. , soils affected by cultivation, deforestation, erosion, and frequent shifts in vegetation because of droughts and rains. Using a full radiative transfer model imbedded in a general circulation model, we find that disturbance dust causes an increase in the global mean radiative forcing by about $0.1\,\mathrm{W\,m^{-2}}$ at the top of the atmosphere, and a decrease of the net surface flux by about $1\,\mathrm{W\,m^{-2}}$, accompanied by increased atmospheric heating that may be a significant forc-